Substantiation of Required Characteristics of the Space-Rocket Complex for Interception of Dangerous Space Objects in the System of Earth Protection

V. A. Volkov, I. I. Velichko,
State Rocket Centre "Makeyev Design Bureau"
Russia

Asteroids and comets with trajectories intersecting the orbit of Earth represent a danger to our planet. The possible ways to prevent a dangerous object from colliding with Earth are splitting or deflecting its trajectory. For that purpose nuclear explosive devices with power up to 10...20 megatons are proposed to be used. The report based on statistical data processing embracing over 100 dangerous asteroids gives a substantiation of required performances of the Space Rocket Interception Complex - the basic component of the Earth Protection System. The calculated time of interception and required initial velocity depending on the time left until collision and efficiency of the available nuclear device are presented. The report shows the possibility of creating an interception complex consisting of a space interceptor with a nuclear explosive device, a booster, a launch-vehicle and supporting systems. The offered complex is able to attack a dangerous object up to several kilometers in diameter, provided the interceptor is launched several years prior to prospective collision. For interception of dangerous objects with diameter of 0.5...1.0 km the interceptor should launch approximately 0.5...1 years prior to collision.

Introduction

At present scientific and technical experts of a number of countries intensively discuss the possible ways of development of the Earth protection system to guard the planet against asteroid-comet danger.

In accordance with the materials of the International Conference "Problems of Earth Protection Against Collision with Dangerous Space Objects" (SPE-94) where these problems were discussed (September 26-30, 1994, Snezhinsk), the system can be developed by the international community in the foreseeable future on the basis of accumulated knowledge and experience in the field of space-rocket, nuclear and common industrial technologies. The basic component of the Earth Protection System is the Space Rocket Interception Complex (SRIC) for interception of Dangerous Space Objects (DSO) - asteroids and comet nuclei.

The report offered to Your notice gives a complex substantiation of required external performances of the SRIC.

Dangerous space objects

Asteroids and comet nuclei with trajectories intersecting the orbit of Earth represent a danger to the Earth's biosphere. Some asteroids approach the Sun closer than Earth and, thus, pose direct threat of collision with the planet.

For substantiation of required performances of the SRIC the accepted predicted characteristics of DSO, their mass and strength properties and space-time characteristics of their orbits are of decisive importance. For this purpose statistical data processing embracing about 200 asteroids was carried out. In the course of the processing it was assumed that the danger of collision with Earth is higher for those asteroids that are closer to the orbit of the planet at the instant of the processing. The results of the processing are presented in Fig.1...6. Fig.1...3 present statistical functions and histograms of distribution of asteroids' diameters, orbit inclinations concerning the ecliptic and periods of revolution around the Sun for a sample of 184 asteroids with perihelia below 1.33 a. u. Fig. 4...6 present the same dependencies for a sample of 91 asteroids (from the aforecited sample) that approach the Earth's orbit closer than 15 mill. km.(0. 1 a.u.). In accordance with the premises taken, in the near future collision is possible with the asteroids having the parameters presented in Fig.4...6, and in the more remote future - the ones presented in Fig.1...3.

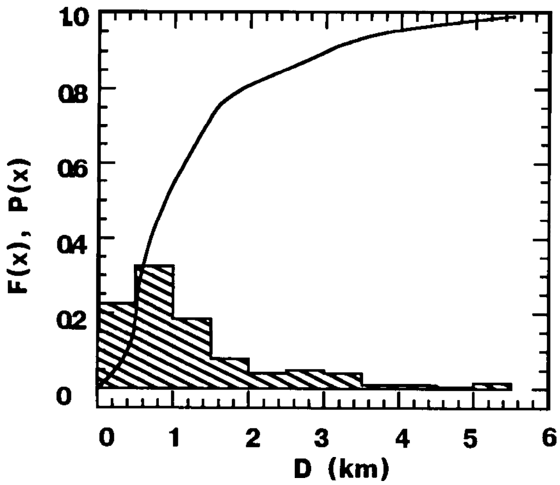

Figure 1. Statistic Function and Distribution Histogram of dangerous asteroids diameter
(the long-term prospect)

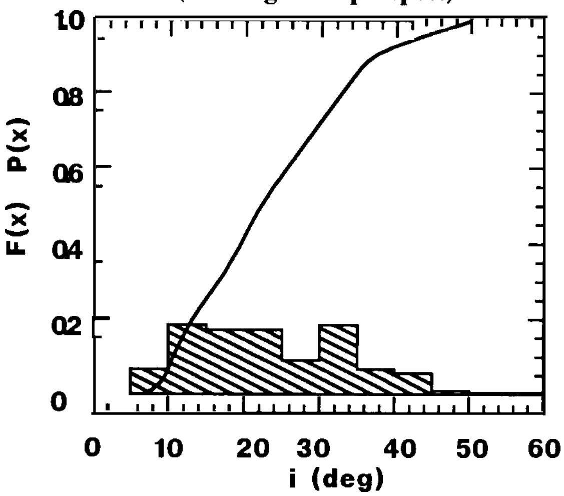

Figure 2. Statistic Function and Distribution Histogram of dangerous asteroids orbit inclination
(the long-term prospect)

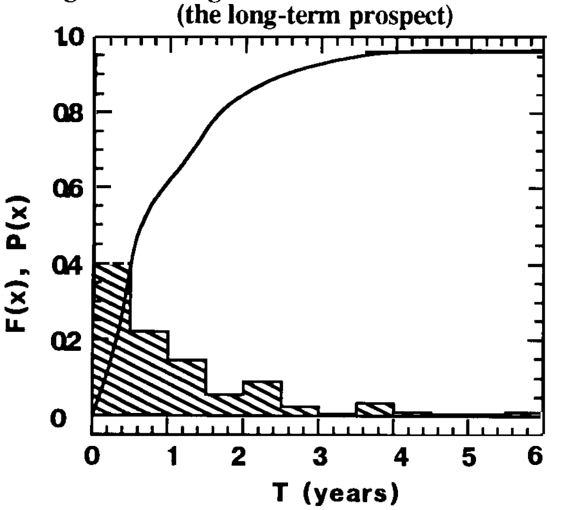

Figure 3. Statistic Function and Distribution Histogram of period of revolution of dangerous asteroids
(the long-term prospect)

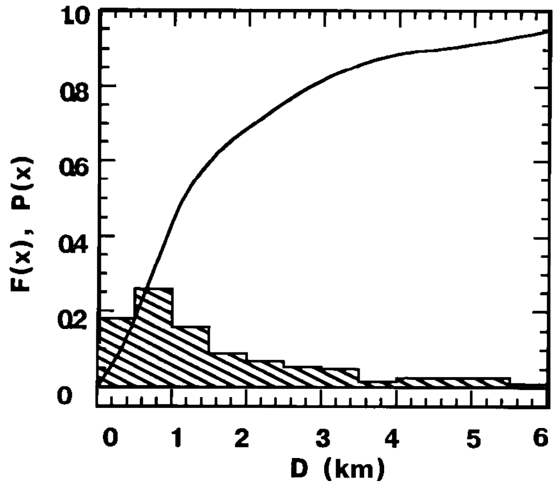

Figure 4. Statistic Function and Distribution Histogram of dangerous asteroids diameter
(the near-term prospect)

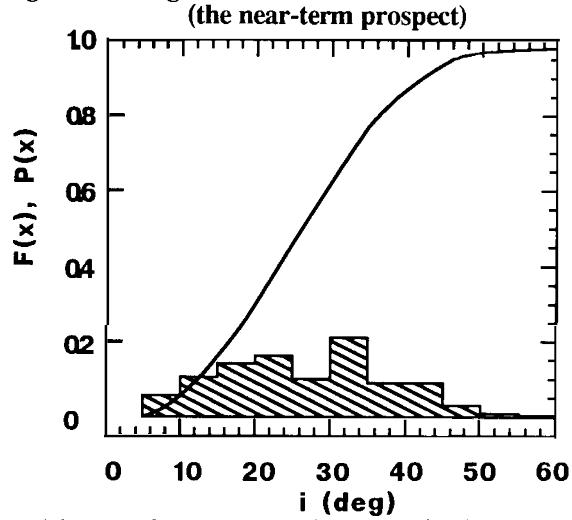

Figure 5. Statistic Function and Distribution Histogram of dangerous asteroids orbit inclination
(the near-term prospect)

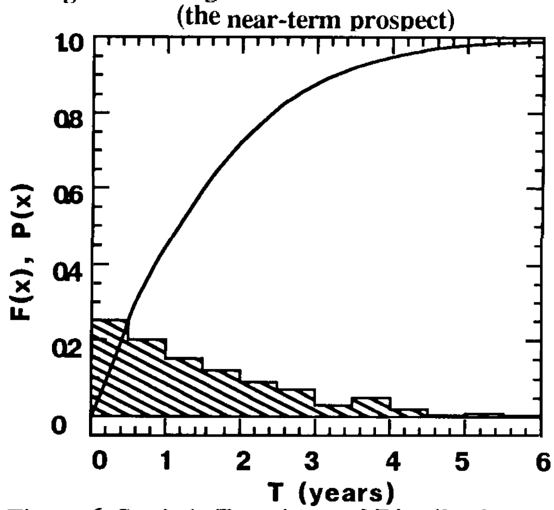

Figure 6. Statistic Function and Distribution Histogram of period of revolution of dangerous asteroids
(the near-term prospect)

Table 1 presents the results of the dependencies analysis for the near-term prospect and Table 2 - those for the long-term prospect.

Table 1. Basic parameters of dangerous asteroids of the near-term prospect.

Level of probability	**Diameter (km)**	**Inclination (deg)**	**Period of revolutions (years)**
F(x) = P{ X<x }=0.5	< 1.0	< 8	< 2.5
F(x) = P{ X<x }=0.9	< 3.0	< 25	< 3.5
Pmax	0.5...1.0	0...5.0	1.0...1.5 3.0...3.5

Table 2. Basic parameters of dangerous asteroids of the long-term prospect.

Level of probability	**Diameter (km)**	**Inclination (deg)**	**Period of revolutions (years)**
F(x) = P{ X<x }=0.5	< 1.2	< 11	< 2.7
F(x) = P{ X<x }=0.9	< 4.5	< 32	< 4.2
Pmax	0.5...1.0	0...5.0	3.0...3.5

In the course of the selection of required performances of the SRIC it is reasonable to take such predicted characteristics of DSO and their trajectories that embrace the whole range of significant characteristics, as a minimum for the near-term prospect, and the worked out performances of the SRIC should later provide the solution to the long-term prospect problems, for example by way of increasing the system power performances.

The space-time trajectory characteristics of the asteroids like Ikar and Adonis (periods of revolution 1.117 and 2.76 years respectively, inclination 0...25 deg.) are assumed to be the most appropriate predicted characteristics of DSO. Taking into account that among known meteos (DSO which have already impacted the Earth and reached its surface) stone chondrites are of absolute majority, as a DSO model substance we will consider a stone silicate material having a density of ca. 3500 kg/m^3 and mechanical properties close to those of rocks on the Earth's surface. The most probable diameter of dangerous asteroids is 0.5...1.0 km, though the possibility of collision with bigger ones, 3.0...4.5 km in diameter, should also be considered.

Possible ways of influence on dangerous space objects

The basic methods to prevent dangerous collision of DSO with Earth are the following:

- deflection of a DSO trajectory to ensure its safe pass by Earth;
- splitting or any other way of disintegration into small fragments of no danger to the Earth's biosphere.

In addition to the objects that collide with Earth directly, the objects "captured" by the Earth's gravitational field when passing at a distance are also dangerous to the planet. Fig.7 presents a DSO capture radius depending on its velocity relative to Earth. The DSO capture radius determines the maximum initial miss of the DSO, relative to Earth considered as a point mass, which leads to its fall onto Earth. If the miss is greater the DSO will not fall onto Earth, though its trajectory will be curved by the planet's gravitational field.

From the plot it is evident that with increase in the DSO relative velocity the value of capture radius decreases and from the values of 20...30 km/sec and on asymptotically approaches the Earth's radius. For the predicted parameters taken (Ikar and Adonis type) the capture radius is about 7000 km. Thus the effect means efficiency (the amount of momentum applied) and the time of advanced action should be determined so as to bring the DSO out of a range of 7000 km from Earth at the instant of the prospective collision. It should be noted that increase in the intercept range leads to essential decrease in the required increment of the DSO velocity. This principle is of decisive importance for determination of the SRIC parameters, its propulsion system capabilities of delivery of the DSO effect means, and for development of appropriate tactical application schemes.

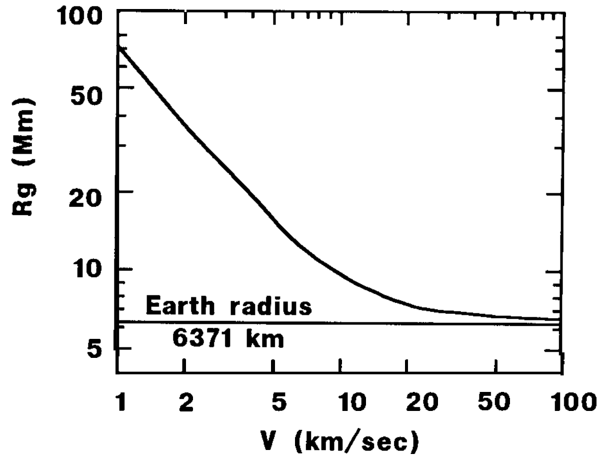

Figure 7. Gravitational capture radius (Rg) dependence of a space object approach velocity (V)

Practical realization of one or another application scheme will in many respects depend on to which extent the information services of the Earth Protection System (EPS) are capable of timely warning about the danger.

Effects produced on space objects by nuclear explosive devices

Complex coordination of the SRIC performances requires data on the DSO velocity increment caused by action of effect means. Nuclear explosive devices are taken as predicted effect means. Their merit is high concentration of energy in a nuclear charge, which allows to use an interceptor of comparatively small mass and dimensions.

The effects produced on a DSO by a nuclear explosion are the following:

- the momentum gained by the object from the shock wave of the explosion products and interceptor fragments;
- reactive forces caused by evaporation of thin superficial layer produced by penetrating radiation;
- reactive forces caused by rock ejection from the crater produced by the explosion;
- shock waves initiated by the explosion within the body of the object.

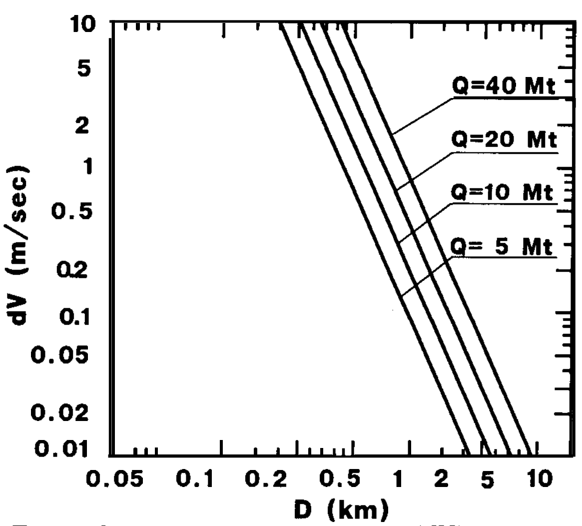

Figure 8. DSO velocity increment (dV), produced by contact explosion of a nuclear device of various power (Q), depending on diameter (D) of DSO with density of 3500 kg/m^3.

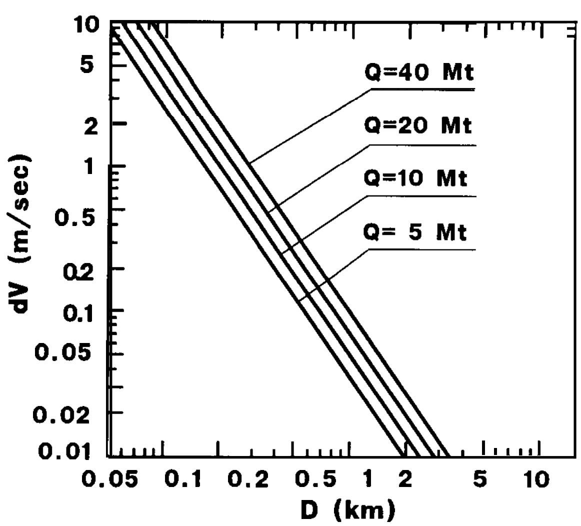

Figure 9. DSO velocity increment (dV), produced by non-contact explosion of a nuclear device of various power (Q), depending on diameter (D) of DSO with density of 3500 kg/m^3.

Fig.8 presents the estimates of velocity increment, gained by an object as a result of contact explosion, depending on the nuclear device power. The calculations show that by way of contact explosion of power 10...20 megatons a velocity increment up to 1 m/sec can be imparted to an asteroid 1.3...2.0 km in diameter.

Fig.9 presents the values of velocity increment, gained by an object as a result of non-contact explosion, depending on the nuclear device power. In this case the altitude of the explosion is accepted so as to produce the maximum velocity increment. The calculations show that by way of non-contact nuclear explosion of power 10...20 megaton a velocity increment up to 1 m/sec can be imparted to an asteroid 200...300 m in diameter.

Estimations of the additional velocities imparted to DSO are obtained using methods available in SRC which are assumed to be further proved by specialized organizations in the next phase of research.

The nuclear devices application efficiency can be greatly improved by implementing deepened explosions within the object body. According to the estimation given by the Russian Federal Nuclear Center (RFNC-VNIITF) only 10...13 % of released energy spreads into the object interior as a result of contact explosion, with the rest of it dissipated into the outer space. With a nuclear charge put at certain optimum depth from 70...80 % to 100 % of the released energy goes into splitting and ejection of rock material. Therefore in this case approximately 7-fold increase in velocity increment of the DSO can be expected as compared with contact explosion of the same nuclear device.

Tactical capabilities of nuclear explosive devices of preventing asteroids from colliding with Earth (tactical interception mode) are adduced in Fig.10. It presents the maximum size of rock asteroids with density of 3500 kg/m^3 that can be brought at the required distance from Earth (about 7000 km) without destruction depending on a nuclear device power, the method used (contact, non-contact, deepened) and advanced action time (the time between the nuclear device explosion and prospective collision with Earth).

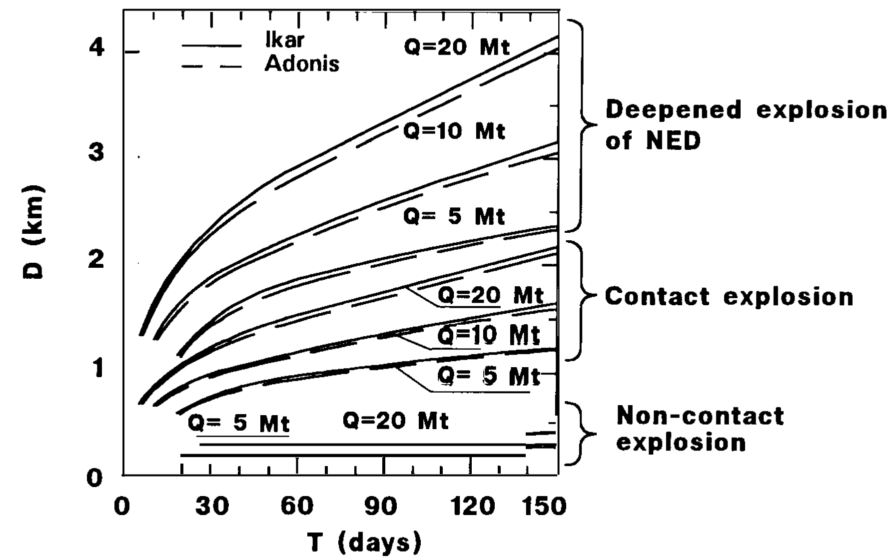

Figure 10. Maximum diameter (D) of DSO that can be brought at safe distance from Earth depending on NED power (Q), method of its application and advanced action time (T).

The analysis of the presented dependencies shows that asteroids belonging to the most probable class (in mass) with diameter of 0.5...1.0 km can be deflected from Earth by means of contact explosion of power 5...20 Mt. In this case the advanced action time can vary between 6...10 days and 80 days depending on the nuclear device power. More powerful nuclear explosive devices (NED) allow lesser advanced action time. Bringing larger asteroids (3...4.5 km in diameter) at safe distance from Earth requires deepened explosions of powerful NED and advanced action time about 120 days.

The alternative way of bringing asteroids away from Earth is strategic interception mode when the interception of a DSO is implemented during several revolutions of the object around the Sun. In this case the required power of NED can be greatly reduced because of the longer advanced action time.

Required parameters of the space interceptor delivery schemes

To obtain the predicted values of initial velocity and time of delivery of the space interceptor (SI) to DSO, which make it possible for the SRIC to implement tactical and strategic interception, the computer simulation of the process of interception was carried out. In the process of the simulation the trajectories requiring the least initial velocities were selected from the whole set of possible trajectories of the SI delivery to the interception point. Fig. 11...14 present the calculated values of initial velocities of the SI and the time

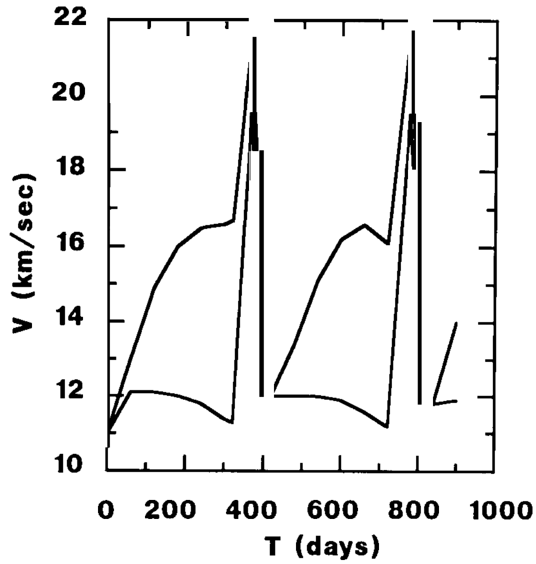

Figure 11. Required initial velocity (V) of SI for interception of an asteroid of Ikar type depending on advanced action time (T).
The upper plot - for the case of interception of an asteroid with orbit inclination of 23 deg. The lower plot - for the case of interception of an asteroid with an orbit lying in the ecliptic plane.

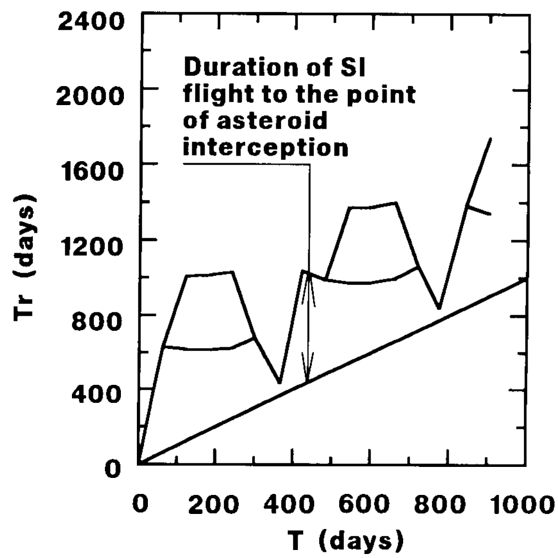

Figure 12. Reserve of time (Tr), necessary for interception of an asteroid of Ikar type, depending on advanced action time (T).
The upper plot - for the case of interception of an asteroid with orbit inclination of 23 deg.
The lower plot - for the case of interception of an asteroid with an orbit lying in the ecliptic plane.

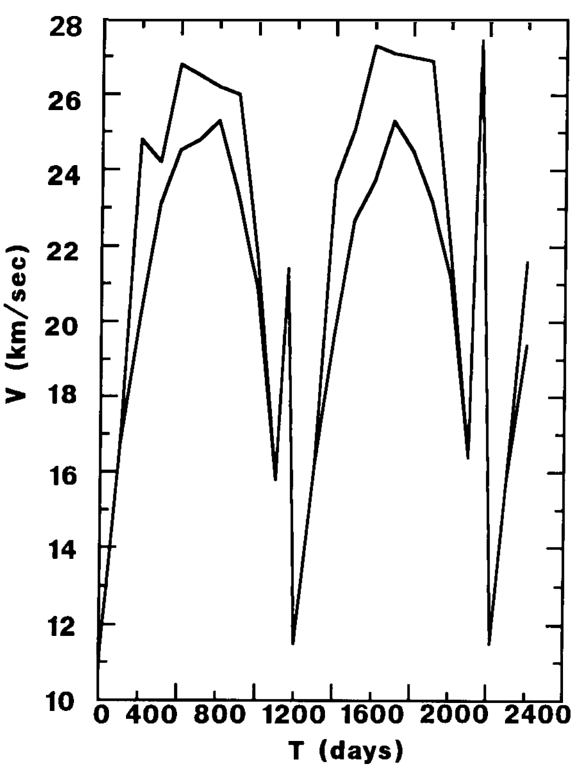

Figure 13. Required initial velocity (V) of SI for interception of an asteroid of Adonis type with orbit inclination of 25 deg depending on advanced action time (T). The upper plot - with maximum duration of the interceptor flight limited by 3 years. The lower plot - with duration of the interceptor flight not limited.

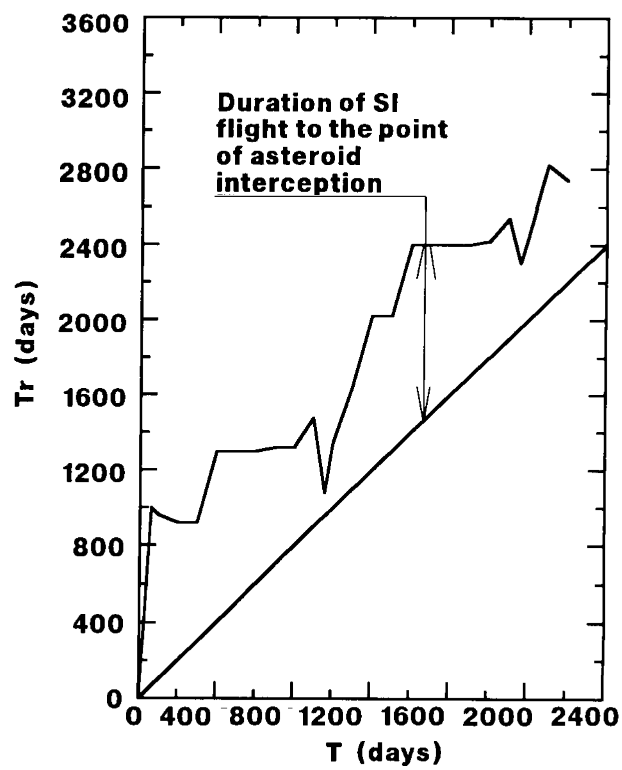

Figure 14. Reserve of time (Tr), necessary for interception of an asteroid of Adonis type with orbit inclination of 25 deg depending on advanced action time (T). Duration of the interceptor flight limited by 3 years.

necessary for tactical interception. These values are given for interception of asteroids of Ikar and Adonis type. The values of required initial velocities and interception time are presented depending on the advanced action time. Besides, time of interception is not limited by capabilities of the EPS information services. The results of calculations for interception of asteroids with diameter 0.5 . . . 1.0 km with the use of NED of power 5...20 Mt are presented in Table 3.

Table 3. Space-time parameters of tactical interception of asteroids with diameter of 0.5...1.0 km with the use of nuclear explosive devices of various power

NED power (Mt)	Time of advanced action (days)	Minimum required velocity of the SI (km/sec)			Time necessary for interception (days)		
5	15...80	11.3-12.1[a]	11.6-13.6[b]	11.6-15.5[c]	200-630[a]	200-760[b]	200-1000[c]
10	10...40	11.2-11.8[a]	11.4-12.3[b]	11.4-13.4[c]	140-420[a]	140-420[b]	140- 660[c]
20	6...20	11.1-11.3[a]	11.2-11.6[b]	11.2-11.6[c]	80-200[a]	80-200[b]	80- 200[c]

[a]Ikar-type asteroid (inclination 0 deg)
[b]Ikar-type asteroid (inclination 23 deg)
[c]Adonis-type asteroid (inclination 25 deg)

The analysis of the presented data shows the following. The use of more powerful NED for interception of asteroids of the most probable class (0.5...1.0 km in diameter) leads to a decrease in the values of required initial velocity of the SI and the time needed for interception.It appears inexpedient to use NED with power of 5 Mt, because in this case interception requires a long period of time (up to 1000 days) and initial velocity up to 15.5 km/sec. As far as these parameters are concerned the use of NED with power of 20 Mt is the most preferable. Nevertheless from the calculations follows that increasing the initial velocity of the SI to 14...15 km/sec makes it possible to increase time of interception in tactical mode up to 1 year even with the use of NED with power of 10 Mt.

The greatest efficiency according to these criteria (lesser initial velocity of the SI and lesser time of interception) can be obtained by using NED with power of 20 Mt. In this case required initial velocity of the SI is not greater than 12 km/sec with time of interception not greater than half a year.

As noted above, it is more preferable from the energetic standpoint to implement interception of the largest asteroids of the near-term and long-term prospects (with diameter up to 3 km and 4.5 km respectively) in the mode of strategic interception, performed at the intersection point of the asteroid and Earth orbits in one or more revolutions of the asteroid around the Sun before its collision with Earth.

Table 4 presents initial velocity and time required for interception with the use of NED with power of 5 Mt, 10 Mt, 20 Mt.

Table 4. Space-time parameters of strategic interception of asteroids with diameter of 3.0...4.5 km with the use of nuclear explosive devices of various power

Diameter of asteroid (km)	NED power (Mt)	Time of interception (years)[a]	Number of DSO revolutions before collision[a]	Initial velocity (km/sec)[a]
3.0	5	5 / 4	3 / 1	11.2 / 11.2
	10	2 / 4	1 / 1	11.1 / 11.2
	20	2 / 4	1 / 1	11.1 / 11.2
4.5	5	9 / 7	7 / 2	11.1 / 11.5
	10	6 / 4	4 / 1	11.4 / 11.2
	20	3 / 4	2 / 1	11.5 / 11.2

[a]Initial velocity of the SI and time of interception adduced in the numerator relate to interception of asteroids with Ikar-type trajectories, and in the denominator - with Adonis-type trajectories.

The presented data show that using NED with power of 5 Mt leads to considerable increase in time of interception, as compared with NED with power of 10 Mt and 20 Mt, which is inexpedient.

The estimations also show that in one revolution around the Sun the asteroids of the following size can be intercepted (see Table 5).

From the presented data follows that the size of the asteroids that can be intercepted in one revolution before collision with Earth exceeds the size of asteroids of the near-term prospect for all considered conditions of interception and NED with power of 10 Mt and 20 Mt. It should also be noted that realization of the SI velocities of 13...14 km/sec can reduce the time necessary for interception of DSO by 0.5 years approximately.

Table 5. Space-time parameters and the maximum diameter of an asteroid, intercepted in strategic mode in one revolution before collision, for nuclear explosive devices of various power.

NED power (Mt)	Time of interception (years)[a]	Initial velocity (km/sec)[a]	Diameter of asteroid (km)[a]
5	2 / 4	11.1 / 11.2	2.4 / 4.4
10	2 / 4	11.1 / 11.2	3.0 / 5.6
20	2 / 4	11.1 / 11.2	3.8 / 7.1

[a]Initial velocity of the SI, time of interception and diameter of asteroid adduced in the numerator relate to interception of asteroids with Ikar-type trajectories and in the denominator - with Adonis-type trajectories.

Interception of large asteroids of the long-term prospect will require from the SRIC and the EPS information services of advanced warning realization of longer time of interception (up to 7...9 years).

Thus, the results of calculations show that the whole list of the problems presented to the SRIC can be successfully solved by realization of tactical and strategic modes of the SRIC application. There are two equally effective variants of the SRIC:

- The SRIC with initial velocity of 14 km/sec and NED with power of 10 Mt;
- The SRIC with initial velocity of 12 km/sec and NED with power of 20 Mt.

Determination of parameters of the space rocket interception complex

Adduced in previous paragraphs of the report conditions of effective application of NED for bringing DSO at a distance eliminating collision with Earth manifest themselves in respect to the delivery means as requirements for the SRIC and determine its external parameters which, in turn, determine its internal parameters and characteristics as well. The basic of these conditions are the following:

- the necessity to ensure direct hit of DSO by NED;
- the necessity to ensure high velocities (up to 12...14 km/sec);
- long interception time.

For the realization of the adduced conditions the SRIC should consist of the following components:

- the space interceptor providing delivery of a nuclear explosive device to the specified point of the DSO surface;
- the booster providing putting the space interceptor with required accuracy into the specified trajectory of flight to DSO;
- the launch-vehicle providing putting the space interceptor with the booster into low Earth orbit;
- the supporting systems of the complex.

When operating together in space the SI and the booster form the Orbital Impact Module (OIM).

The functional scheme of the SRIC is presented in Fig.15.

The achieved level of development of space-rocket technologies allows to form an image of the SRIC from the most developed and accomplished systems, that enable the complex to solve the problems set to it.

For above considered NED with power of 10 Mt and 20 Mt Table 6 presents mass parameters of the SI, the booster operating on criogen components ($H_2 + O_2$) or having electric propulsion systems, and mass parameters of the whole OIM. A circular orbit with altitude of 200 km is taken as the basic (initial) orbit.

Table 6. Mass parameters of the space interceptor, the booster and the whole Orbital Impact Module for NED of various power

NED power (Mt)	Initial velocity (km/sec)	Mass of the SI (tons)	Mass of the booster (tons)[a]	Total mass of the OIM (tons)[a]
10	14.0	9.5	55.5 / 27.0	65 / 36.5
20	12.0	17.6	42.4 / 33.4	60 / 51

[a]Mass of the booster operating on criogen fuel $H_2 + O_2$ and corresponding to this booster total mass of the OIM are adduced in the numerator, and the same parameters for the booster with Electric Rocket Propulsion System (of TEM “Bars” type) - in the denominator.

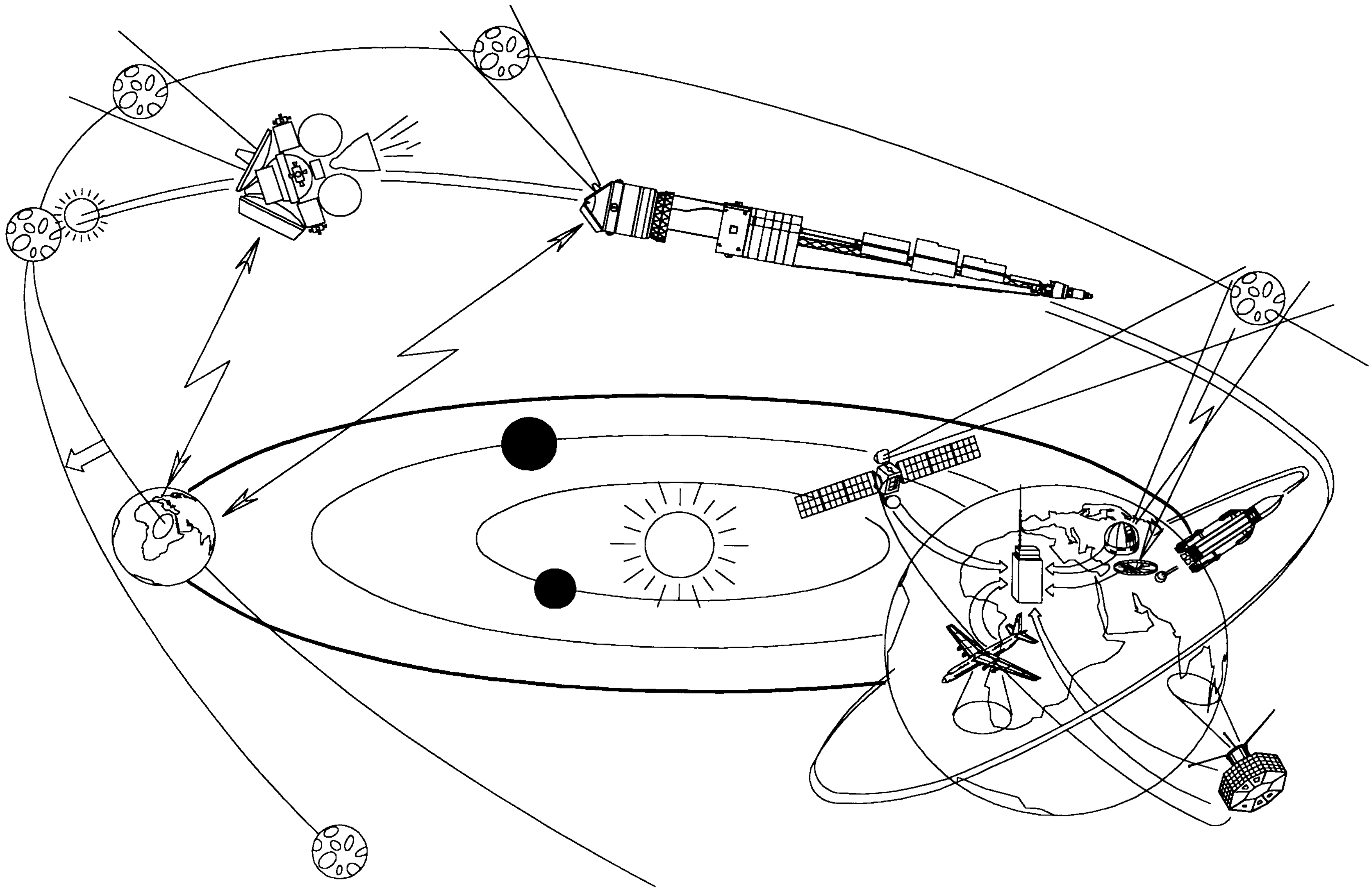

Figure 15. Functioning scheme of the Earth Protection System

According to our preliminary estimations, in the near-term prospect the space interceptors carrying nuclear charges with power of 10 Mt and 20 Mt for contact and non-contact application can be developed, as well as the boosters on criogen fuel components for the SRIC of the first generation that can solve the problems of the near-term prospect.As the OIM launch vehicle the "Energia" (at present the only launch-vehicle in the world capable of putting a payload of the required mass into low Earth orbit) possesses the highest degree of the availability.

The use of nuclear energized electric propulsion systems in the OIM makes possible an increase in the mass of the payload serving for interception, which allows to provide energy supply for realization of long interception time, that may be more preferable for interception of DSO of the long-term prospect, especially with the use for these purposes of alternative high-efficient non-nuclear effect means. The estimations show that the use of ERPS (Electric Rocket Propulsion Systems) makes possible delivery of the SI with a mass up to 42 tons (with a mass of the OIM about 100 tons) to DSO in the strategic mode of interception.

Conclusion

The carried out research allowed to form the image of the SRIC, based on the up-to-date achievements in space-rocket and nuclear technologies, that should become a basis for development of the system for protection of Earth against asteroid-comet danger.

This requires synchronous deployment of scientific research, design and experimental works for development of the basic systems of the EPS - the SRIC and the information services, and for creation of a catalogue of dangerous space objects and revision of space-time, mass and strength parameters of DSO.